

A new low mass for the Hercules dSph: the end of a common mass scale for the dwarfs?

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ABSTRACT

We present a new mass estimate for the Hercules dwarf spheroidal galaxy (dSph), based on the revised velocity dispersion obtained by Adén et al. (2009).

The removal of a significant foreground contamination using newly acquired Strömgren photometry has resulted in a reduced velocity dispersion. Using this new velocity dispersion of $3.72 \pm 0.91 \text{ km s}^{-1}$, we find a mass of $M_{300} = 1.9_{-0.8}^{+1.1} \times 10^6 M_\odot$ within the central 300 pc, which is also the half-light radius, and a mass of $M_{433} = 3.7_{-1.6}^{+2.2} \times 10^6 M_\odot$ within the reach of our data to 433 pc, significantly lower than previous estimates. We derive an overall mass-to-light ratio of $M_{433}/L = 103_{-48}^{+83} [M_\odot/L_\odot]$. Our mass estimate calls into question recent claims of a common mass scale for dSph galaxies.

Additionally, we find tentative evidence for a velocity gradient in our kinematic data of $16 \pm 3 \text{ km s}^{-1} \text{kpc}^{-1}$, and evidence of an asymmetric extension in the light distribution at $\sim 0.5 \text{ kpc}$. We explore the possibility that these features are due to tidal interactions with the Milky Way. We show that there is a self-consistent model in which Hercules has an assumed tidal radius of $r_t = 485 \text{ pc}$, an orbital pericentre of $r_p = 18.5 \pm 5 \text{ kpc}$, and a mass within r_t of $M_{\text{tid},r_t} = 5.2_{-2.7}^{+2.7} \times 10^6 M_\odot$. Proper motions are required to test this model. Although we cannot exclude models in which Hercules contains no dark matter, we argue that Hercules is more likely to be

1. Introduction

Dwarf spheroidal (dSph) galaxies are believed to play an important role in the formation and evolution of much more luminous galaxies (e.g. Gallagher & Wyse 1994). dSphs are characterized by their low surface brightness, low total luminosity and spheroidal shapes which are consistent with their pressure-supported stellar kinematics (e.g. Grebel et al. 2003).

Knowledge of dSph masses is essential for comparison with cosmological simulations of galaxy formation. Good mass estimates help us to establish whether the paucity in the number of observed systems (a few tens) to the number of predicted satellite haloes (several thousands) represents a fundamental failure of our cosmological model (e.g. Moore et al. 1999), or whether it is simply telling us that galaxy formation is inefficient on small scales (e.g. Read et al. 2006a). Recent studies have suggested that the dSph galaxies share a common mass within a certain radius (Walker et al. 2007; Strigari et al. 2008; Walker et al. 2009). If confirmed, this would be an important clue to the processes which regulate the formation of the lowest luminosity galaxies.

All mass estimates implicitly assume that contamination of the kinematic sample by foreground stars or unbound tidal tails is negligible, and that the system is in (or close to) virial equilibrium. Since the mass of an equilibrium stellar system is proportional to its velocity dispersion squared, an over-estimate of the velocity dispersion will result in an inflated mass estimate. The assumption of virial equilibrium may be called into question if the system is tidally disrupting (Oh et al. 1995; Kroupa 1997; Klementowski et al. 2007; Muñoz et al. 2008).

The recently discovered Hercules dSph (Belokurov et al. 2007), with an ellipticity of $e \sim 0.5$ (Coleman et al. 2007), is an example of a galaxy in which assumptions of equilibrium may be incorrect. In Adén et al. (2009) we showed that the mean velocity of the Hercules dSph is embedded in the foreground dwarf star velocity distribution. In order to weed out the foreground dwarf stars we used the Strömgren c_1 index. This index is able to clearly identify red-giant branch (RGB) stars redder than the horizontal branch, enabling a separation of RGB stars in the dSph galaxy and

foreground dwarf stars. By weeding out the foreground contaminants we found that the dispersion for Hercules is reduced from $7.33 \pm 1.08 \text{ km s}^{-1}$ to $3.72 \pm 0.91 \text{ km s}^{-1}$. In this letter we explore the consequences of this finding.

In Section 2, we derive a new mass for Hercules and show that it is not consistent with a common mass scale for the dSphs. In Section 3, we investigate the possibility of a velocity gradient in the kinematic data of Hercules. In Section 4, we discuss the relative importance of tides and dark matter in Hercules. Section 5 summarises our conclusions.

2. Mass estimate from the spherical Jeans equations

We use the velocity dispersion, $\sigma_v = 3.72 \pm 0.91 \text{ km s}^{-1}$ (Adén et al. 2009), to constrain the mass of the Hercules dSph. We assume that the system is in dynamical equilibrium, is spherically symmetric, has an isotropic velocity distribution, and a flat velocity dispersion profile¹. With these assumptions, the Jeans equation for the mass distribution (Eq. (4.215) in Binney & Tremaine 2008) becomes:

$$\sigma_v^2 \frac{d\nu(r)}{dr} = -\frac{\nu(r) G M(r)}{r^2} \quad (1)$$

where r is the three-dimensional distance from the centre of the galaxy, $\nu(r)$ is the de-projected stellar density profile and $M(r)$ is the enclosed mass. We use the exponential profile from Martin et al. (2008) to describe the stellar density profile. The de-projected exponential profile is given by Klementowski et al. (2007) as (setting $m = 1$ in their Eq. (4)):

$$\nu(r) = \nu_0 \left(\frac{r}{\alpha} \right)^{-0.445} e^{-r/\alpha} \quad (2)$$

where α is the exponential scale radius, related to the half-light radius as $r_h = 1.68\alpha$, and ν_0 is the central stellar density. Solving Eq. (1) for $M(r)$ using Eq. (2) yields

$$M(r) = \frac{r(r + 0.445\alpha)\sigma_v^2}{\alpha G} \quad (3)$$

¹Note that Wolf et al. (2009) and Walker et al. (2009) find that their mass estimates at the half light radius are insensitive to a wide range of mass models and velocity anisotropy parameterisations, so our results should not be sensitive to these assumptions.

Using a half-light radius of 330_{-52}^{+75} pc (Martin et al. 2008) we solve Eq. (3) for $r = 433$ pc, which corresponds to the outermost member in our kinematic sample (Table 1).

We estimate the error in the mass using 10^5 Monte Carlo realisations of the half-light radius, distance and velocity dispersion of Hercules drawn from within the individual error bars on each parameter. In this way, we obtain $M_{433} = 3.7_{-1.6}^{+2.2} \times 10^6 M_\odot$ (Fig. 1). The quoted errors are $1-\sigma$ limits from the Monte Carlo sampling. Assuming a total luminosity of $L = (3.6 \pm 1.1) \times 10^4 L_\odot$ (Martin et al. 2008), we find a median mass-to-light ratio of $M_{433}/L = 103_{-48}^{+83} [M_\odot/L_\odot]$.

Adén et al. (2009) emphasise the importance of weeding out foreground, contaminating dwarf stars. This is particularly vital for the Hercules dSph as its systemic velocity coincides with the bulk motion of dwarf stars in the Milky Way disk in the direction of Hercules. Using the contaminated² velocity dispersion (Table 1) we would obtain a mass of $1.4_{-0.4}^{+0.5} \times 10^7 M_\odot$, almost a factor of four larger than the uncontaminated estimate.

2.1. Hercules and the “Common Mass Scale”

Strigari et al. (2008) speculate that the mass within a fixed radius, 300 pc, is approximately the same ($\sim 10^7 M_\odot$) in all the observed dSphs. Our revised velocity dispersion implies a mass within the inner 300 pc (M_{300}) of only $1.9_{-0.8}^{+1.1} \times 10^6 M_\odot$. This indicates that Hercules falls considerably below this “common mass scale” for dSphs. Since 300 pc is also approximately the half-light radius, this implies that Hercules also lies significantly off the Walker et al. (2009) enclosed half-light mass scaling relation.

To confirm that our result is not sensitive to our choice of surface brightness profile, we have repeated our calculation using a Plummer profile with scale radius $r_{pl} = 321$ pc (as used by Strigari et al. 2008). In this case we find $M_{300} = 2.3 \times 10^6 M_\odot$ in agreement with the mass calculated above. If instead we use our contami-

²Note that this “contaminated” dispersion has had its 3σ velocity outliers removed. Also, the initial candidate selection for the velocities were chosen using colour-magnitude diagram cuts. Even so, a significant fraction of foreground stars remain in this sample and are detected only through the use of the Strömgren photometry.

nated velocity dispersion and the exponential surface density profile, we obtain $M_{300} = 7.4_{-2.1}^{+2.7} \times 10^6 M_\odot$ which agrees with the value presented in Strigari et al. (2008).

However, we note that Strigari et al. (2008) used a dispersion of $5.1 \pm 0.9 \text{ km s}^{-1}$ (taken from Simon & Geha 2007) to obtain their mass estimate. This is smaller than our contaminated value of $7.33 \pm 1.08 \text{ km s}^{-1}$, yet they obtain a similar median mass to us. If we use a dispersion of $5.1 \pm 0.9 \text{ km s}^{-1}$ as they do, we obtain a mass $M_{300} = 3.6_{-1.2}^{+1.5} \times 10^6 M_\odot$. This is just consistent with their determination within our mutual error bars. We note that the median M_{300} will depend on the details of the mass modelling procedure and so can be expected to differ between their study and ours (Matt Walker priv. comm.).

Additionally, we have repeated our calculation of the mass within 300 pc using a more recent estimate of the half-light radius, $r_h = 230$ pc, by Sand et al. (2009). This half-light radius is smaller and gives a mass that is ~ 1.5 times more massive than the mass calculated using the half-light radius from Martin et al. (2008).

3. A velocity gradient in Hercules

The presence of a velocity gradient in a dSph could either be indicative of an intrinsic rotation, or a sign of tidal interaction with the Milky Way. In this section, we test for possible velocity gradients in Hercules.

Assuming that the rotation around the semi-minor axis (in the ellipse that describes the orientation of the dSph) is more likely than around the semi-major axis we can define the “semi-minor axis distance” $d_{mi}(\theta)$ as the distance, perpendicular to the semi-minor axis, between the axis and the star. For each of the 18 RGB stars with radial velocities we calculate this distance for different position angles θ . We then derive the gradient, k_{rot} , and zeropoint, m_v , by solving the following equation with a least-squares fit for each position angle,

$$V_{\text{rad}} = k_{\text{rot}} \times d_{mi}(\theta) + m_v \quad (4)$$

where V_{rad} is the radial velocity measurement for each stars. The least-squares fit to this function yields a χ^2 value for each θ (Fig. 2a).

The distribution enclosed by $\chi^2_{\text{min}} + 1$ corresponds to 1σ for a normal distribution (Press et al.

1992). We use this to obtain the error in the position angle which minimizes χ^2 .

We find a position angle of -35^{+18}_{-23} degrees with a velocity gradient of $16 \pm 3 \text{ km s}^{-1}\text{kpc}^{-1}$, and a zeropoint of $45.11 \pm 0.38 \text{ km s}^{-1}$. We obtain a reduced χ^2 of 3.89 for our 18 stars with 2 degrees of freedom.

Following Walker et al. (2008), we estimate the significance of the velocity gradient using 10^5 Monte Carlo realisations. In each realisation, we sample the velocity and spatial distributions independently. Thus we scramble the correlation between velocity and position, while maintaining the original velocity distribution and spatial positions. This is valid as long as the phase space distribution function of the stars is separable (which implies that the velocity dispersion is independent of radius). We determine the significance of the velocity gradient by computing the fraction of realisations that fail to produce a χ^2 as low as the one calculated from the real data. We find a significance of the velocity gradient of 78 per cent (1.23σ).

4. Discussion

4.1. Galactic tides in Hercules?

In the previous section we found tentative evidence for a velocity gradient in the Hercules dSph. The peak-to-peak difference of $\sim 10 \text{ km s}^{-1}$ within a radius of less than 1 kpc could be interpreted as the effect of Galactic tides (Read et al. 2006b). Interestingly, Martin (2009) recently estimated the orbit of Hercules based on the assumption that its elongation is tidally induced, and predicted a velocity gradient of at least $7 \text{ km s}^{-1}\text{kpc}^{-1}$ which is consistent with our observed gradient. Additionally, in Adén et al. (2009) we found that the spatial distribution of the Hercules stars is asymmetric at ~ 0.5 kpc. There are three significant outlier stars to the South, but no corresponding members at this distance in either the Northern or Western fields (Fig. 3). These three stars are unambiguously identified as RGB stars from Strömgren photometry. We now consider the possibility that the velocity gradient and the positional outliers are evidence that Hercules is being tidally disrupted, and use this information to obtain a second mass estimate for the system.

The tidal radius of a dSph depends on the

potential of the host galaxy, the potential of the dSph, the orbit of the dSph within the host galaxy and the orbit of the stars within the dSph (e.g. Read et al. 2006c). We parameterise the Milky Way potential using the default model in Johnston et al. (2005), analysed in the Galactic plane; and the Hercules potential using a generalised Hernquist profile (Hernquist 1990):

$$\rho(r) = \frac{M(3-\gamma)}{4\pi r_s^3} \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{\gamma-4} \quad (5)$$

where M is the total mass, r_s the scalelength, and γ the central logarithmic cusp slope. We consider the ranges $0.3 < r_s < 3 \text{ kpc}$ and $0 < \gamma < 1$. Our results are not sensitive to these choices.

The orbit of the Hercules dSph is unknown but it currently lies at a distance of 132 kpc from the galactic centre, and has a heliocentric velocity of $45.2 \pm 1.09 \text{ km s}^{-1}$, which implies a galactocentric radial velocity of $145 \pm 1.09 \text{ km s}^{-1}$ (see Eq. (5) in Courteau & van den Bergh 1999). Using the above potential model for the Milky Way and setting the tangential velocity component for Hercules to zero, this gives us a minimum apocentre for Hercules of $r_{a,\min} = 188.5 \text{ kpc}$. Thus, we consider apocentre and pericentre ranges of $188.5 < r_a < 600 \text{ kpc}$ and $5 < r_p < 132 \text{ kpc}$, respectively.

Read et al. (2006c) find that photometric features are typically seen beyond the retrograde tidal radius. To proceed, we make the assumption that the outliers in Fig. 3 indicate the location of the retrograde tidal radius of Hercules, i.e. $r_t \sim 485 \text{ pc}$. If we assume further that the tidal radius of Hercules is set at the pericentre of its orbit, we can solve Eq. (7) of Read et al. (2006c) to calculate the mass, M_{tid} , of Hercules as a function of its orbital pericentre r_p , for our assumed ranges of r_s , γ and r_a . We calculate both its mass within r_t (M_{tid,r_t}) and its mass within 433 pc ($M_{\text{tid},433}$) which can then be compared with our mass estimate based on the spherical Jeans equation ($M_{\text{SJ},433}$). The results of this calculation are given in Fig. 4. The horizontal light grey band marks $M_{\text{SJ},433}$, the dark grey band marks $M_{\text{tid},433}$ and the medium grey band marks M_{tid,r_t} . The vertical solid and dashed lines mark the pericentres at which $M_{\text{tid},433} = M_{\text{SJ},433}$. The width of the tidal mass bands is due to the unknowns: r_s ,

γ , and r_a . However, to lowest order r_t depends only on the mean density enclosed within it, and so these bands are narrow. For this reason, we obtain an estimate of both the orbital pericentre of Hercules ($r_p = 18.5 \pm 5$ kpc) and its mass within the tidal radius ($M_{\text{tid},r_t} = 5.2^{+2.7}_{-2.7} \times 10^6 M_\odot$). The primary source of error on both of these quantities is our assumed tidal radius r_t . Empirically we derive scalings of:

$$r_p = 32 \left(\frac{r_t}{1 \text{ kpc}} \right)^\beta \text{ kpc} \quad (6)$$

with $\beta = 0.76$ over the range $r_t = [0.4, 2]$ kpc, and:

$$M_{\text{tid},r_t} = 24 \times 10^6 \left(\frac{r_t}{1 \text{ kpc}} \right)^\alpha M_\odot \quad (7)$$

with $\alpha = 2.1$ over the same range.

If we assume $r_t = 485$ pc, we obtain a similar estimate of the pericentric distance as that obtained by Martin (2009).

4.2. Is Hercules a dark matter free system?

We have shown that our Hercules data are consistent with the presence of dark matter. We now consider whether models without dark matter could also reproduce the data.

The most extreme scenario is that Hercules is disintegrating and its velocity dispersion arises solely due to the motion of its unbound member stars. If so, it will rapidly become unobservable (i.e. reach a lower surface brightness than the detection limit of the SDSS). Hercules has a surface brightness of 27.2 ± 0.6 mag arcsec $^{-2}$ (Martin et al. 2008). If the unbound stars are moving away from Hercules at a velocity equal to the velocity dispersion (3.72 ± 0.91 km s $^{-1}$) it would require only $\sim 200 \times 10^6$ years for the Hercules dSph to fall below the detection limit of SDSS (~ 30 mag arcsec $^{-2}$ Koposov et al. 2008). Given this short timescale, it is very unlikely that we would observe Hercules at this phase of its evolution.

Fellhauer et al. (2007) simulated the disruption of the UMa II dSph. Using a model that does not distinguish between luminous and dark matter they simulate the surface brightness, velocity dispersion and the mean radial velocity for UMa II after 9, 10 and 11 Gyr (their Fig. 9).

In the absence of dark matter, the equilibrium velocity dispersion (i.e. $\sigma^2 = G M/r$) for the Hercules dSph would be ~ 1 km s $^{-1}$, assuming a stellar mass of $5 \times 10^4 M_\odot$ and a radius equal to the observed half-light radius (300 pc; Martin et al. 2008). This is much lower than the measured velocity dispersion of 3.72 ± 0.91 km s $^{-1}$. We conclude that the Hercules dSph can only be a dark matter free system if its velocity dispersion has been inflated significantly - i.e. if it is in the advanced stages of tidal disruption.

However, in the simulations of Fellhauer et al. (2007) the evolutionary phase in which a tidal remnant exhibits both an inflated velocity dispersion and a velocity gradient, and remains centrally concentrated is very short. Within ~ 1 Gyr the system goes from bound, with almost no signs of tidal disturbance, to complete disruption.

(We note that Kroupa (1997) performed simulations of dSph galaxies without dark matter, and found that it is possible to obtain long-lived remnants whose properties are remarkably similar to those of Hercules in terms of velocity dispersion and velocity gradient (see his Fig. 9). However, the remnants simulated by Kroupa (1997) are significantly more luminous than the Hercules dSph. Based on the simulations of Fellhauer et al. (2007), it seems unlikely that lower luminosity, purely stellar remnants with the correct properties could survive for a significant time.)

It seems difficult to understand Hercules without dark matter. However, it could be dark matter dominated *and* experiencing significant tidal disturbance. In this case, our simple Jeans analysis may have over-estimated its mass and Hercules might lie even further away from a possible common mass scale for the dSph galaxies.

5. Conclusions

We have calculated the mass of the Hercules dSph using the new velocity dispersion for the system obtained by Adén et al. (2009). We find that the mass within the volume enclosed by our observed stars is $3.7^{+2.2}_{-1.6} \times 10^6 M_\odot$, leading to a mass-to-light ratio of $103^{+83}_{-48} [M_\odot/L_\odot]$. Interestingly, the mass within 300 pc is significantly lower than the “common mass scale” found by Strigari et al. (2008), suggesting that Hercules does not share the halo properties seen in other dSphs.

We found tentative evidence for a velocity gradient of $16 \pm 3 \text{ km s}^{-1} \text{kpc}^{-1}$, and evidence of an asymmetric extension in the light distribution at $\sim 0.5 \text{ kpc}$. We explored the hypothesis that these features are due to tidal interactions with the Milky Way. Assuming a tidal radius of 485 pc , we show that a self-consistent model requires Hercules to be on an orbit with pericentre $r_p = 18.5 \pm 5 \text{ kpc}$, and with a mass within r_t of $M_{\text{tid},r_t} = 5.2^{+2.7}_{-2.7} \times 10^6 M_\odot$.

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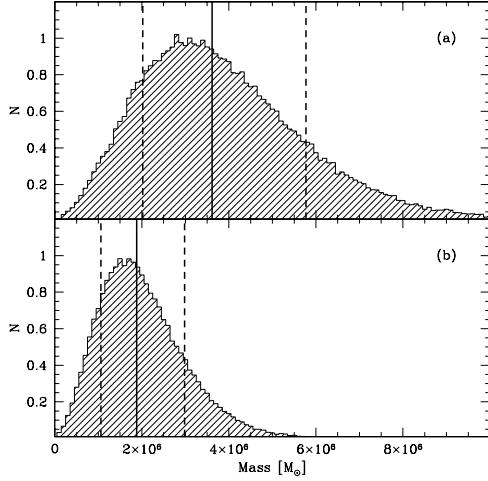


Fig. 1.— Distribution of Monte Carlo mass estimates for Hercules. Solid line indicates the median from the Monte Carlo sampling. Dashed lines indicate the 1σ limits from the Monte Carlo sampling. (a) Mass within the radius defined by the outermost RGB star in the kinematic sample, $r = 433$ pc. (b) Mass within the inner 300 pc.

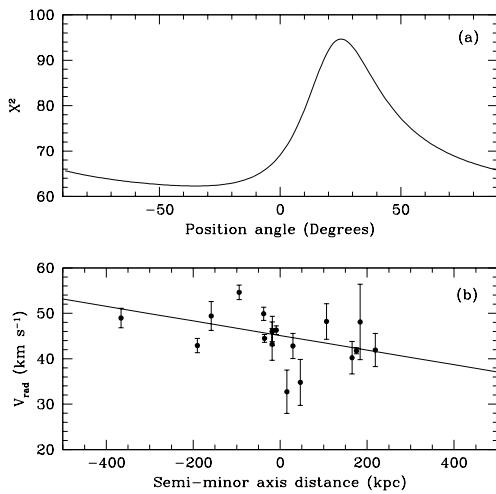


Fig. 2.— (a) χ^2 vs. the position angle. (b) V_{rad} vs. semi-minor axis distance. The solid line indicates the least-square fit. • indicates members based on Strömgren photometry (see Adén et al. 2009).

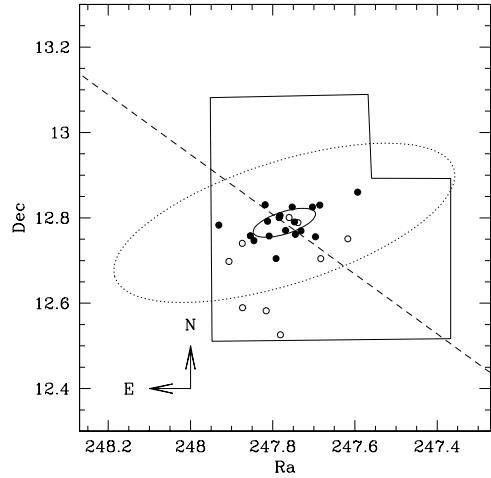


Fig. 3.— Spatial distribution on the sky of the stars identified as Hercules members from both spectroscopy and photometry. ○ indicate members based on Strömgren photometry. • indicate members based on Strömgren photometry for which there are radial velocity measurements. The dashed line indicates the semi-minor axis for the position angle of our detected rotation axis. The solid ellipse represents the core radius and the dotted ellipse the inner border of the field region of the Hercules dSph (Coleman et al. 2007). Solid lines outline the footprint of the WFC used to obtain the Strömgren photometry.

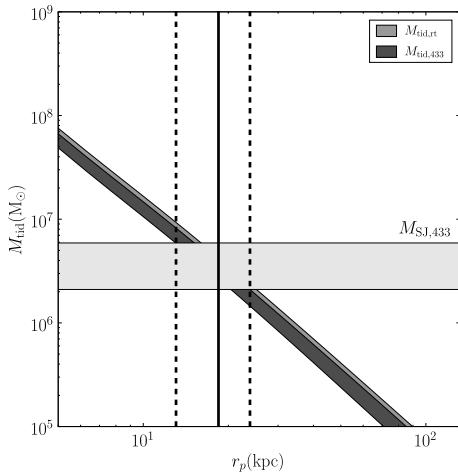


Fig. 4.— Tidally determined mass for Hercules as a function of orbital pericentre r_p . We assume a retrograde tidal radius of $r_t = 1$ kpc for this calculation. The horizontal grey band marks our mass estimate from the spherical Jeans equation $M_{\text{SJ},433}$ (See Sect. 2). The dark grey band marks our tidally determined mass within 433 pc $M_{\text{tid},433}$ for Hercules. The medium grey band shows M_{tid,r_t} , our tidally determined mass within r_t . The vertical solid and dashed lines mark the pericentres at which $M_{\text{tid},433} = M_{\text{SJ},433}$ (see Eq. 6 for a formula giving the scaling of M_{tid,r_t} with r_t).

TABLE 1
SUMMARY OF DETERMINATION OF SYSTEMIC VELOCITIES, VELOCITY DISPERSIONS, MASSES AND METALLICITIES FOR THE HERCULES DSPh.

	Number of stars	v_{sys} [km s $^{-1}$]	σ [km s $^{-1}$]	M _{Furthest star} [M_{\odot}]	M _{300pc} [M_{\odot}]	$\langle [Fe/H] \rangle$ dex	^a
Adén et al. (2009)	28 [RGB stars, c_1 sel.]	-	-	-	-	-2.35 ± 0.31	
This study	32 [Only V_{rad} sel.]	40.87 ± 1.42	7.33 ± 1.08	$1.4_{-0.4}^{+0.5} \times 10^7$	$7.4_{-2.1}^{+2.7} \times 10^6$	-	
This study	18 [RGB stars with V_{rad}]	45.20 ± 1.09	3.72 ± 0.91	$3.7_{-1.6}^{+2.2} \times 10^6$	$1.9_{-0.8}^{+1.1} \times 10^6$	-	

^aSee Adén et al. (2009)

NOTE.—Columns: (1,2) number of stars in each study and a short description of how the stars were selected; (3,4) systemic velocities and velocity dispersions; (5) mass within the radius defined by the outermost RGB star in our study; (6) mass within the inner 300 pc; (7) mean metallicity [see Adén et al. (2009) for a full discussion of metallicities].